Consider IGBTs over power MOSFETs at frequencies to 100 kHz

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Evaluating the performance of IGBTs and high-voltage power MOSFETs for switching applications requires a common set of applications and assumptions. Comparisons of maximum current vs frequency reveal that IGBTs are competitive at frequencies as high as 100 kHz.

Choosing a device to use as a power switch is one of the most difficult decisions facing a power-converter designer. Data sheets provide most of the necessary information to make an informed decision. However, different manufacturers' data sheets don't necessarily contain the same information or present it in the same way. Also, the information in the data sheet may not be a direct fit with your application. Often, you have to do some additional calculations and extrapolation.

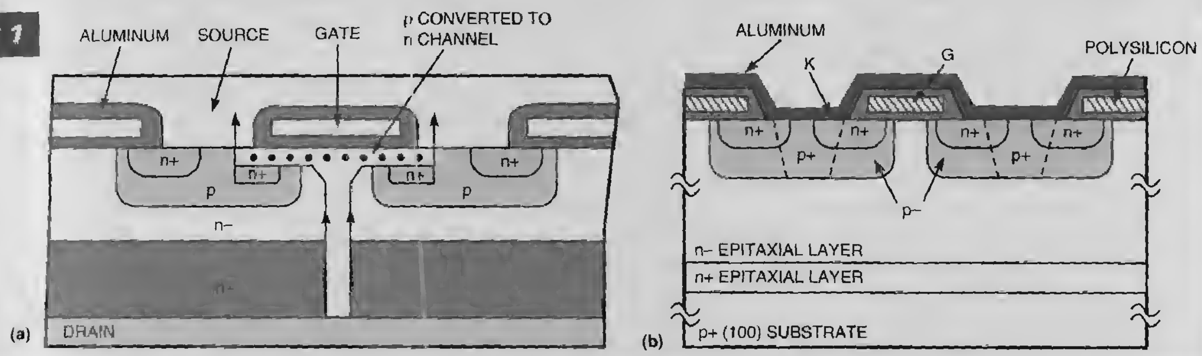
Fortunately, you can directly compare a number of high-voltage power MOSFETs and insulated-gate bipolar transistors (IGBTs) by making some realistic assumptions for the most common applications and then calculating the maximum current each device can safely switch at various frequencies.

The IGBT is a powerful competitor of the power MOSFET, particularly at lower frequencies. The IGBT, with substantially higher current densities and lower $R_{DS(ON)}$ across the operating-temperature range, is a good alternative to MOS switches requiring high-voltage performance. Slowly, the IGBT has evolved into new-generation offerings with higher operating frequencies and lower saturation voltages. Now, you can control the bipolar fall-time tail, and IGBTs with standard operating frequencies of 50 kHz at rated current are available.

Furthermore, comparisons of IGBT and power-MOSFET performance show that you can extend an IGBT's operating range well beyond 50 kHz. The circuit configuration of the power converter affects the maximum frequency at which an IGBT can outperform a power MOSFET, but the maximum frequency is greater than 100 kHz in many cases. In most applications of power switches to 100 kHz, the IGBT is a better choice. For applications with frequencies as high as 100 kHz, an IGBT can handle more current at high voltages than the same-size power MOSFET.

Before directly comparing IGBTs and power MOSFETs,

FIGURE 1



Although the differences between the vertical structure of a power MOSFET (a) and that of an IGBT (b) are small, these differences have a major effect on the devices' characteristics. For instance, the n-type substrate of power MOSFETs and p-type substrate of IGBTs result in a difference of $R_{DS(ON)}$.

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however, you need to understand the differences in their physical structure and how these differences affect their performance and application. To perform comparison tests, you also need to make some underlying assumptions and choose comparable data-sheet values.

Structure determines current

Although the difference in the vertical structure of the IGBT and power MOSFET is small, this difference has a major effect on the characteristics of the two devices. The substrate (bottom layer) of the IGBT is p-type silicon, whereas the power MOSFET uses n-type silicon (**Figure 1**). In the power MOSFET, the relatively thick region labeled n– in **Figure 1** provides voltage-breakdown resistance. This wide layer of high resistivity results in a high series resistance when the power MOSFET is on.

The IGBT requires just as thick a layer of high-resistivity material to provide voltage-breakdown resistance. However, because the substrate is p-type material, biasing the IGBT on causes the injection of minority carriers (electrons) into the substrate. This minority-carrier injection reduces the resistivity of the n– region just as if the device were constructed of lower resistivity silicon, temporarily lowering the forward-voltage drop by as much as a factor of 10. The conduction losses in any application all decrease proportionately.

Reduce the minority-carrier lifetime

When the gate-drive circuit biases the IGBT off, the minority carriers that reduce the forward-voltage drop continue to lessen the resistivity of the n– layer until these carriers recombine. In silicon that has a long minority-carrier lifetime, this process can take on the order of tens of microseconds. If fabrication didn't involve lifetime reduction in the n– region, IGBTs would be suitable for switching only the slowest applications.

TABLE 1—IGBT AND POWER-MOSFET RATINGS AND DIE DIMENSIONS

Size	600V UFS IGBTs (w×l in.)	600V power MOSFETs (w×l in.)	250V power MOSFETs (w×l in.)
1	HGTP3N60C3 (D) (0.074×0.098)		IRF614 (0.067×0.087)
2	HGTP7N60C3 (D) (0.092×0.141)	IRFBC20 (0.084×0.139)	IRF624 (0.091×0.102)
3	HGTP12N60C3 (D) (0.126×0.182)	IRFBC30 (0.116×0.180)	IRF634 (0.116×0.181)
4	HGTP20N60B3 (D) (0.160×0.240)	IRFBC40 (0.170×0.227)	IRF644 (0.162×0.219)
4		IRFPC40 (0.170×0.227)	
5		IRFPC50 (0.257×0.257)	IRFP254 (0.257×0.257)
6		IRFPC60 (0.260×0.360)	IRFP264 (0.257×0.360)

ASSUMPTIONS AND APPROXIMATIONS FOR CALCULATIONS

1. For all three conditions of antiparallel-diode conduction:

A. All calculations use data-sheet values and the stated maximum if available. If the maximum number is unavailable, the calculations use 120% of the typical value.

B. The case-to-air thermal resistance is 1°C/W, which implies an external heat sink.

C. Ambient temperature is 85°C.

D. Maximum junction temperature is 150°C.

E. The energy due to switching losses in the diode flows through the thermal resistance of the power MOSFET or IGBT.

F. The duty cycle is 50%.

G. Gate drive is the data-sheet specification for switching-time measurements.

H. Switching losses are proportional to supply voltage and collector or drain current.

I. The calculations ignore conduction losses in the antiparallel diode.

J. Turn-off energy for the power MOSFET is

$$\frac{I_D \bullet V_{DD} \bullet 1.2 \bullet t_f}{2},$$

where I_D is drain current V_{DD} is the supply voltage (also V_{CE} and V_{CC}), and t_f is the current fall time.

K. Reverse-bias (leakage) dissipation is negligible.

2. For body-diode conduction (in power MOSFETs) and antiparallel diode-conduction:

A. The stored charge, Q_{RR}, in the body diode at 150°C is equal to three times the 25°C-specified value from the data sheet.

B. All the energy that dissipates during turn-on flows through the thermal resistance of the switch.

3. For external series and shunt diodes (in power MOSFETs) and antiparallel-diode conduction:

A. The calculations assume that power MOSFETs use the same diode that the D version of the UFS IGBT uses.

B. The calculations ignore the forward-voltage drop of the series diode.

4. For no antiparallel-diode conduction:

A. Turn-on energy is

$$\frac{t_{ri} \bullet V_{DD} \bullet I_C}{2},$$

where t_{ri} is the current rise time, and I_C is the IGBT collector current, which is analogous to the drain current, I_D, for a MOSFET.

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However, IGBT manufacturers accomplish lifetime "killing" of the minority carriers by radiating the device with high-energy electrons, gamma rays, or fast neutrons or by diffusing a heavy metal, such as platinum, into the device. (A stabilizing anneal must follow these treatments to provide a stable operating life.) Any of these lifetime-reduction approaches makes the IGBT faster but also increases the forward-voltage drop. You must optimize the trade-off between forward-voltage drop and switching speed for your application.

Antiparallel diodes have an effect

Because of their fabrication, power MOSFETs each have an intrinsic diode connected between their drain and source. This diode's polarity is such that it bypasses the MOSFET whenever you reverse-bias the MOSFET. Although IGBTs have no intrinsic diodes, an external antiparallel diode is convenient, even essential, in many circuits.

Most power converters use bridge or half-bridge circuits. In these circuits, the antiparallel diodes, whether internal or external, conduct for a part of each cycle. Each time the circuit biases the diodes on, the body of the diode floods with carriers. Each time the circuit reverse-biases the diode, the circuit must absorb the carriers that exist in the body of the diode at the full power-supply voltage, resulting in appreciable circuit loss.

In high-voltage power MOSFETs, the intrinsic body diode is made of the same material as the MOSFET, which results in long reverse-recovery times. Of course, you can prevent the body diode of a power MOSFET from conducting by adding external series and shunt diodes, but these components add cost, forward-voltage drop, and complexity to the circuit.

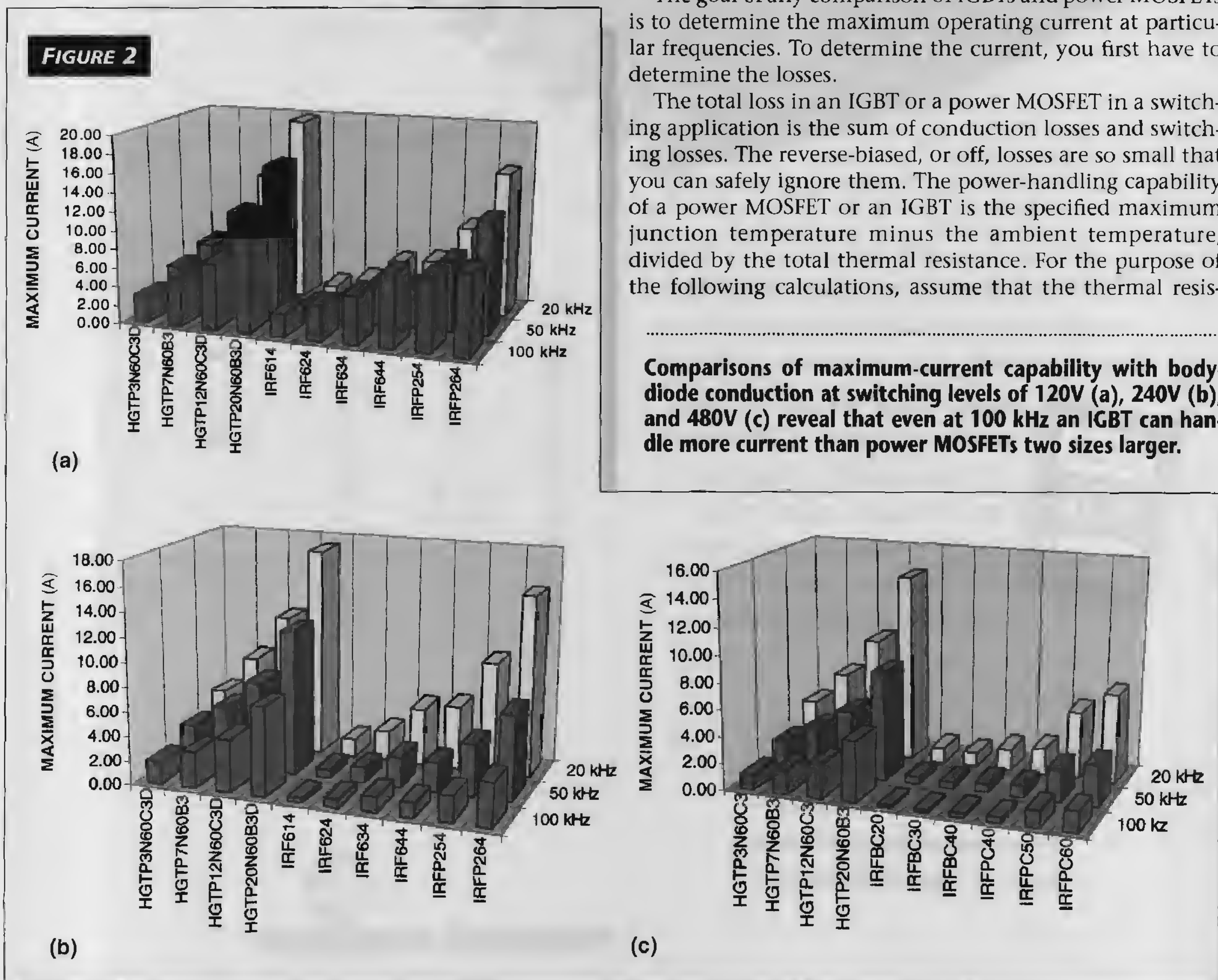
Alternatively, you can select the external diode of an IGBT for low reverse-recovery time. Often, manufacturers can include the external diode in the same package as the IGBT, providing a three-terminal device that is as easy to use as a power MOSFET.

Find the maximum operating current

The goal of any comparison of IGBTs and power MOSFETs is to determine the maximum operating current at particular frequencies. To determine the current, you first have to determine the losses.

The total loss in an IGBT or a power MOSFET in a switching application is the sum of conduction losses and switching losses. The reverse-biased, or off, losses are so small that you can safely ignore them. The power-handling capability of a power MOSFET or an IGBT is the specified maximum junction temperature minus the ambient temperature, divided by the total thermal resistance. For the purpose of the following calculations, assume that the thermal resis-

FIGURE 2



Comparisons of maximum-current capability with body-diode conduction at switching levels of 120V (a), 240V (b), and 480V (c) reveal that even at 100 kHz an IGBT can handle more current than power MOSFETs two sizes larger.

tance external to the power device (heat sink plus interface thermal resistance) is 1°C/W.

Conduction losses are the product of the duty cycle, the forward drop of the device, and the current. The forward drop of the power MOSFET equals the current through the device multiplied by its $R_{DS(ON)}$ at the maximum junction temperature. Data sheets specify the forward drop of the IGBT at the maximum junction temperature, but the drop varies with current and is nonlinear. A good approximation is a 0.4V offset in series with sufficient resistance to equal the specified maximum forward-voltage drop at the maximum junction temperature. The calculations for the comparisons presented here use this approach and assume a 50% duty cycle. The calculations for losses in power MOSFETs that use external series and shunt diodes to prevent body-diode conduction do not include the dissipation in the series diode. Switching losses are the sum of turn-on and -off losses. IGBT data sheets specify these losses at the maximum junction temperature but give only typical values. For calculating the curves in this article, assume that maximum losses are 120% of the typical values in the data sheets. Switching losses are approximately proportional to voltage and current. Keeping the antiparallel diode—either internal or external—from conducting reduces but doesn't eliminate turn-on losses. You can assume that the turn-on loss for this condition for both IGBTs and power MOSFETs is equal to

$$\frac{V_{DD} \bullet I \bullet t_{ri}}{2},$$

where V_{DD} is the supply voltage, I is the current, and t_{ri} is the current rise time.

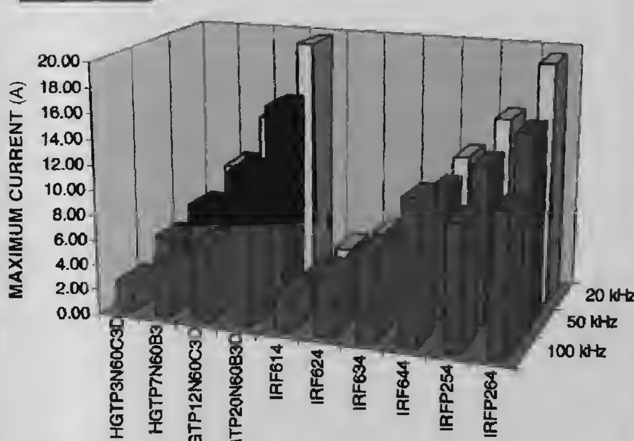
The data sheets of power MOSFETs don't usually specify switching losses but do specify switching times. Because switching times vary little with temperature in power MOSFETs, you can use the 25°C value as maximum junction temperature. The data sheets usually give fall times for the 10 to 90% points, so using a factor of 1.2 to estimate the complete fall time is valid. The loss for turn-off is approximately equal to

$$\frac{V_{DD} \bullet I \bullet t_f \bullet 1.2}{2},$$

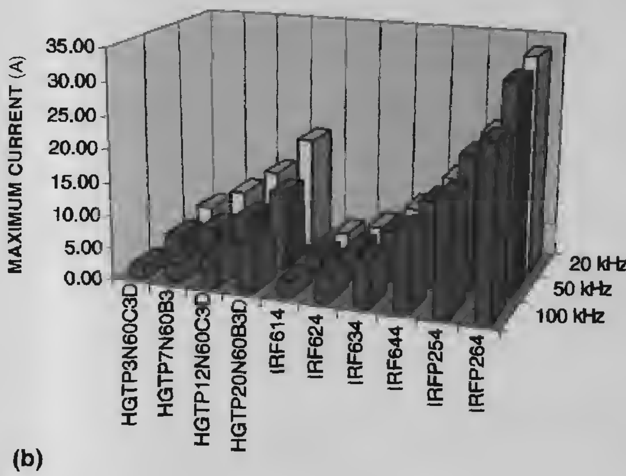
where t_f is the fall time. You can calculate turn-on losses for the condition when you do not allow the diode to conduct in the same way you calculate these losses for IGBTs.

To calculate turn-on loss when the diode conducts, you need to know the diode characteristics. When the antiparallel diode conducts, the circuit must absorb the stored charge

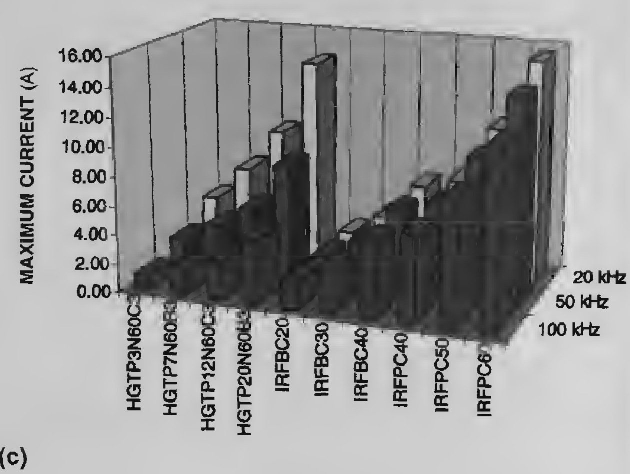
FIGURE 3



(a)



(b)



(c)

Comparisons of maximum-current capability with external antiparallel-diode conduction at switching levels of 120V (a), 240V (b), and 480V (c) show that at 50 kHz, an IGBT can handle more current than the same-size power MOSFET. At 100 kHz, a power MOSFET can handle more current.

in the diode (the minority carriers launched into the high-resistivity region during conduction) at the full supply voltage. The switch, whether it's an IGBT or a power MOSFET, absorbs about three-fourths of this energy, and the diode absorbs the remainder. For this comparison, assume that all the energy dissipates in the switch.

A power-MOSFET data sheet specifies the stored charge in the diode, Q_{RR}, at 25°C. At 150°C, this charge increases by about a factor of 3. Turn-on energy per switch is

$$\frac{Q_{RR}(\text{TYPICAL AT } 25°\text{C}) \bullet 1.2 \bullet 3 \bullet V_{DD} \bullet I_C}{I_{MEASURE}},$$

where I_C is the collector current and $I_{MEASURE}$ is the current at which Q_{RR} is measured. Switching power dissipation is the total switching energy per switch multiplied by the frequency of operation. When you use a series and a shunt diode with a power MOSFET to avoid body-diode conduction, for purposes of comparison, assume that the hyperfast diode is the same as that for the IGBT calculations.

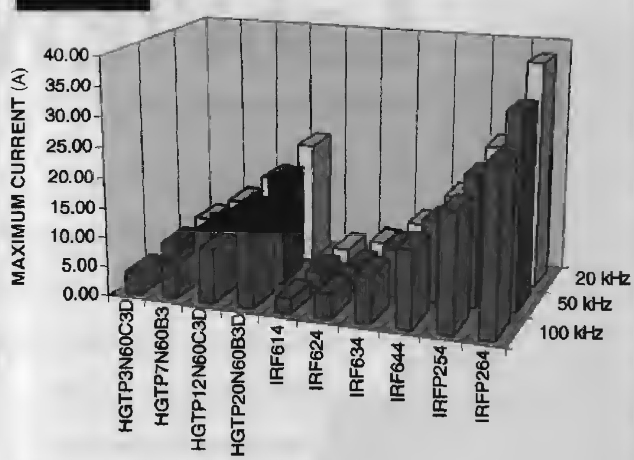
Power transistors, both power MOSFETs and IGBTs, usually come in sizes 1 through 6 (**Table 1**). Although devices vary slightly within each size category, comparisons between devices with the same size are realistic. Harris' ultrafast-switching (UFS) IGBT series has a 600V breakdown voltage, and this article compares the calculated maximum current of these IGBTs at switching voltages of 120, 240, and 480V with the maximum current of 250V power MOSFETs at 120 and 240V and with the maximum current of 600V power MOSFETs at 480V. The comparisons include 120 and 240V switching because they are the most common rms voltage levels in North America. (Obviously, to operate the 250V power MOSFET in a practical circuit, you must provide some means to avoid subjecting the devices to more than 250V.)

To calculate the maximum current at 20, 50, and 100 kHz, you have to make certain assumptions (see box "Assumptions and approximations for calculations"). Based on these assumptions, the calculations are straightforward, except that you must adjust the operating current to result in a 150°C junction temperature. You can do this adjustment either by successive approximation or by using the goal function in an Excel spreadsheet.

To calculate the maximum current,

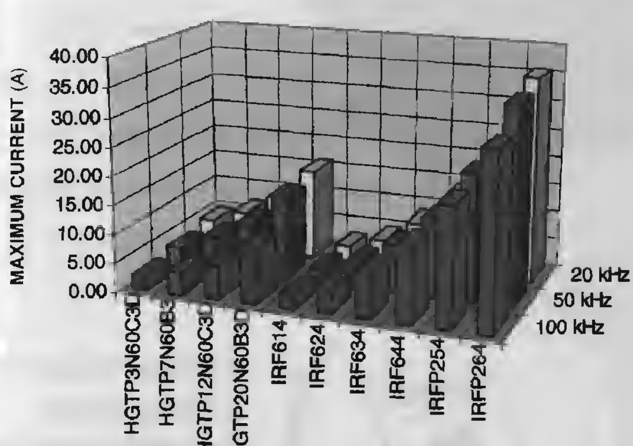
1. Guess an operating current;
2. Calculate the conduction loss;
3. Calculate the turn-off energy per switch;
4. Calculate the turn-on loss per switch;
5. Total the switching energy;
6. Multiply the switching energy by the frequency;

FIGURE 4

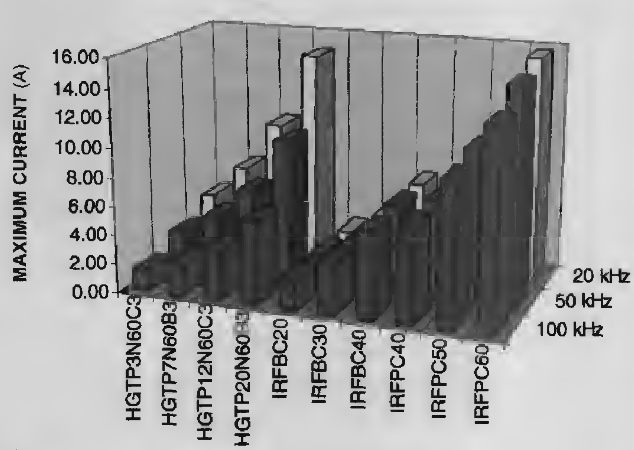


(a)

Comparisons of maximum-current capability with no antiparallel-diode conduction at switching levels of 120V (a), 240V (b), and 480V (c) show that an IGBT can handle more current in some situations (120V switching at 100 kHz) and a power MOSFET can handle more current in others (both 240 and 480V switching at 100 kHz).



(b)



(c)

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7. Total the losses;
8. Multiply the total loss by the maximum junction-to-case thermal resistance plus 1°C/W;
9. Add the ambient temperature (85°C);
10. If the resulting junction temperature is less than 150°, repeat with a greater operating current. If the resulting junction temperature is greater than 150°C, repeat with a lower operating current; and
11. Perform iterations until the results differ from 150°C by less than 0.1°C.

Graphical results of these calculations compare the performance of power MOSFETs to IGBTs under three conditions: with body-diode conduction (**Figure 2**), which is the most common application; with external antiparallel-diode conduction (**Figure 3**); and with no antiparallel-diode conduction (**Figure 4**). The graphs in parts **a** and b of each **figure** compare 600V IGBTs with 250V power MOSFETs while switching at 120 and 240V. Part **c** compares 600V IGBTs with 600V power MOSFETs at 480V.

From these results, you can draw several conclusions. First, if you allow the body diode of the power MOSFET to conduct, a UFS 600V IGBT can handle as much current as a 600 or 250V power MOSFET at least two sizes larger for frequencies through 100 kHz (**Figure 2**). A two-size increase equates to approximately a doubling in silicon die area. Second, if you use an external series and shunt diode with the power MOSFET, a UFS 600V IGBT can handle more current than the same-size power MOSFET through 50 kHz (**Figure 3**). At 100 kHz, a power MOSFET can handle more current than the same-size UFS IGBT.

Finally, you can also conclude that in those applications in which no antiparallel diode conduction occurs, a UFS IGBT operates at a higher current than the same-size power MOSFET through 50 kHz (**Figure 4**). At 100 kHz and both 240 and 480V, a power MOSFET can handle only slightly more current than the UFS IGBT of the same size. At 100 kHz and 120V, the UFS IGBTs outperform the 250V power MOSFETs. EDN

Authors' biographies

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